Long-Term Effects of Clipping and Nitrogen Management in Turfgrass on Soil Organic Carbon and Nitrogen Dynamics: The CENTURY Model Simulation

Y. L. Qian,* W. Bandaranayake, W. J. Parton, B. Mecham, M. A. Harivandi, and A. R. Mosier

ABSTRACT

Experiments to document the long-term effects of clipping management on N requirements, soil organic carbon (SOC), and soil organic nitrogen (SON) are difficult and costly and therefore few. The CENTURY ecosystem model offers an opportunity to study long-term effects of turfgrass clipping management on biomass production, N requirements, SOC and SON, and N leaching through computer simulation. In this study, the model was verified by comparing CENTURY-predicted Kentucky bluegrass (*Poa pratensis* L.) clipping yields with field-measured clipping yields. Long-term simulations were run for Kentucky bluegrass grown under home lawn conditions on a clay loam soil in Colorado. The model predicted that compared with clipping-removed management, returning clippings for 10 to 50 yr would increase soil C sequestration by 11 to 25% and nitrogen sequestration by 12 to 28% under a high (150 kg N ha^{-1} yr^{-1}) nitrogen (N) fertilization regime, and increase soil carbon sequestration by 11 to 59% and N sequestration by 14 to 78% under a low (75 kg N ha^{-1} yr^{-1}) N fertilization regime. The CENTURY model was further used as a management supporting system to generate optimal N fertilization rates as a function of turfgrass age. Returning grass clippings to the turf–soil ecosystem can reduce N requirements by 25% from 1 to 10 yr after turf establishment, by 33% 11 to 25 yr after establishment, by 50% 25 to 50 yr after establishment, and by 60% thereafter. The CENTURY model shows potential for use as a decision-supporting tool for maintaining turf quality and minimizing negative environmental impacts.

Fertilization is one of the major management components in maintaining aesthetically appealing turfgrass in our urban and suburban landscapes. Urban landscapes account for approximately 10% of all fertilizer N used in the USA (Food and Agricultural Organization, 2002; USEPA, 1999). Improper N fertilization may lead to negative environmental impacts, including nitrate leaching and gaseous loss of nitrogen as N_2O, NO_x, and NH_3. Nitrate leaching directly affects ground water quality. Nitrous oxide (N_2O) is a greenhouse gas with 310 times greater global warming potential than CO_2 on a per molecular basis over a 100-yr time frame (Intergovernmental Panel on Climate Change, 1997). The current IPCC national inventory methodology for estimating N_2O emissions from soils relates N_2O emissions to fertilizer input, that is, about 2% of N_2O loss for nitrogen added as fertilizer (Intergovernmental Panel on Climate Change, 1997; Mosier et al., 1998). Nitric oxide (NO) and nitrogen dioxide (NO_2) (NO_x = NO + NO_2) emissions contribute to acidification of precipitation and local air quality problems while ammonia (NH_3) volatilization is an N loss mechanism that distributes N across the landscape. To meet the demand for environmentally friendly urban landscapes, turf scientists have been challenged to provide management strategies that reduce the use of synthetic fertilizer, while providing aesthetically appealing turf.

Turfgrass produces a large amount of clippings every year (Harivandi et al., 2001). Clipping removal from turf represents a major N loss. However, clippings are often removed from lawns because clippings can be unsightly and may contribute to disease and thatch build up (Harivandi et al., 2001). With increasing landfill restrictions on yard waste and efforts to minimize resource input to turfgrass systems, recycling clippings via a mulching mower is becoming a common practice. Several studies have been conducted to determine the impact of clipping management on turf quality and N requirements. Heckman et al. (2000) demonstrated that the amount of applied N could be cut in half (from 195 to 98 kg N ha^{-1} yr^{-1}) when clippings were recycled. Starr and DeRoo (1981) observed that 30% of the total N applied could be saved via clipping return. Recently, Kopp and Guillard (2002) reported that turf plots receiving 0 to 98 kg N ha^{-1} yr^{-1} with clippings returned produced a comparable quality and clipping yields to plots that received 390 kg N ha^{-1} yr^{-1} with clippings removed, suggesting that returning clippings could reduce N fertilization by 75% or more without reducing turf quality. The discrepancies in the degree of reduced N requirements when clippings are returned may have resulted because of the duration of the experiments, site conditions, and initial SOM levels. Although the above studies have examined the effects of clipping return on turfgrass growth, N requirements, and turf quality, no research has documented the effects of clipping management on ecosystem consequences including changes in soil organic carbon (SOC), soil organic nitrogen (SON), and N leaching.

Nitrogen availability in the soil is a dynamic process. Nitrogen in clippings returned to a turf system is not available to turfgrass until it is incorporated into SOM

Y.L. Qian and W. Bandaranayake, Department of Horticulture and Landscape Architecture, Colorado State University, Fort Collins, CO 80523-1173. W.J. Parton, Natural Resource Ecology Laboratory (NREL), Colorado State University, Fort Collins, CO 80523-1173. B. Mecham, Northern Colorado Water Conservancy District, Loveland, CO 80539. M.A. Harivandi, University of California Cooperative Extension, Alameda, CA 94502. A.R. Mosier, USDA-ARS, Soil–Plant–Nutrient Research Unit, Fort Collins, CO 80522. Received 14 Dec. 2002. *Corresponding author (yaqian@lamar.colostate.edu).

Published in J. Environ. Qual. 32:1694–1700 (2003).

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: SOC, soil organic carbon; SOM, soil organic matter; SON, soil organic nitrogen.

and released via mineralization. Mineralized N can be tied up by soil microorganisms (immobilization). The mineralization and immobilization are both controlled by C to N ratio. Therefore, dynamics of N are controlled by C transformation. The effect of clipping management on N and C interrelation is complicated by other management components, such as irrigation and fertilization. This makes it difficult to capture the intertemporal interactions and carryover effects with single-period static analysis. The long-term experiments necessary to fully assess the influence of clipping management on SOC and SON content are difficult and costly. Computer simulation modeling is therefore a useful means of studying potential impacts of alternative clipping management on N requirements and SOC and SON content.

CENTURY is a multicompartmental ecosystem model developed to simulate long-term changes in soil organic carbon and nitrogen, nutrient cycling, and plant production for the soil–plant ecosystem of U.S. Great Plains grasslands (Parton et al., 1987). The model has been well validated and successfully applied to various ecosystems (including pasture, agriculture, and other native systems) in various locations around the world (including tropical and temperate regions) (Kelly et al., 1997; Parton et al., 1993; Parton and Rasmussen, 1994; Carter et al., 1993). CENTURY operates on a monthly time step and is adequate for simulation of medium- to long-term (10 to >10 000 yr) changes in SOC and other ecosystem parameters in response to changes in climate, land use, and management.

Previously, we used CENTURY to simulate SOC changes in response to turfgrass management in golf courses and found that the model is sensitive to both location and soil texture (Bandaranayake et al., 2003). Predictions of SOC accumulation by the CENTURY model compared very well with compiled historical SOC data (R^2 ranged from 0.67–0.83), suggesting that CENTURY is able to simulate SOC changes in managed turfgrass scenarios.

The CENTURY model has not yet been used to simulate the impacts of turfgrass clipping management on fertilization requirements and SOC and SON dynamics. The objectives of this work were to (i) fit the CENTURY model to turfgrass systems and to compare the CENTURY-predicted clipping yields with measured clipping yields from a 3-yr field experiment in northern Colorado; (ii) predict the long-term impacts of clipping management (clippings returned vs. clippings removed) and N fertilization rates on biomass production, SOC and SON content, and N leaching; and (iii) use the CENTURY model as a supporting tool for generating N requirements as a function of turfgrass standing age under clippings returned vs. clippings removed management scenarios.

MATERIALS AND METHODS

Field Experiment

From 1993 to 1995, a study was conducted on 8-yr-old Kentucky bluegrass plots at the Northern Colorado Water Conservancy District research site near Fort Collins, CO. The prior land use of the area was agricultural. The soil was a Fort Collins loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalf; 29% clay, 54% sand, and 17% silt). Slow-release fertilizer (23 N, 3 P, 11 K) was applied in April, May, and October to provide 185 kg N ha^{-1} yr^{-1}. Irrigation was scheduled every 3 to 5 d to apply the amount of water equivalent to approximately 100% evapotranspiration (ET) based on the Kimberly Penman ET model. Plots (3 by 3 m) were mowed weekly to a height of 5.1 cm from May to October; clippings were collected to determine dry weight. On a similar site (8-yr-old Kentucky bluegrass plots), core samples (6 cm in diameter and 60 cm deep) were taken in June and July to determine the biomass of verdure (stubble), thatch, and roots.

Based on the work of Falk (1976, 1980), total annual biomass production was calculated as: total annual production = accumulative clipping yield + biomass of verdure × verdure turnover rate (0.56) + biomass of thatch × thatch turnover rate (0.54) + root biomass × root turnover rate (0.54). We used the average turnover rates derived by Falk (1976, 1980) for Kentucky bluegrass. Percentage of standing aboveground biomass being removed during each mowing event was calculated by dividing clipping yield by the biomass of verdure plus clipping yield of one mowing event.

CENTURY Model Description

Version 4.0 of the CENTURY model (Metherell et al., 1993) was adopted for the turfgrass ecosystem and used for simulating clipping yield, biomass production, and soil C and N dynamics. The detailed description of the CENTURY model has been presented by Parton et al. (1987, 1993). Briefly, the CENTURY model includes a (grassland) production submodel, soil organic matter submodel, N submodel, and soil water balance submodel.

In the grassland production submodel, production is defined by potential aboveground production, root to shoot ratio, and the effects of soil water, temperature, nitrogen availability, and C to N ratios and lignin contents of biomass pools. Default vegetation parameterizations are available with the CENTURY model. We used the default potential aboveground production of 250 g C m^{-2} yr^{-1} in the simulations. The major compartments of turfgrass production are clippings, verdure (stubble), thatch (a layer of living and dead organic matter at the soil surface), and roots. The lignin content of thatch is usually much higher (17–19%) than that of shoots but similar to that of roots. For convenience in the simulation, we treated thatch separately from aboveground tissue. Mowing events were simulated using the Harvest 100 file in the CENTURY model. Based on our field biomass collection data (Table 1), we arrived at a fixed C allocation; about 52% of annual plant production is allocated to aboveground growth (clippings and verdure) and 48% to belowground production (thatch and roots). Four percent of aboveground standing biomass was cut off during each weekly mowing (i.e., about 16% total aboveground biomass was removed on monthly basis). The other modifications made to default parameterizations included altering lignin content of tissue samples (6% for clippings and shoot, 18% for thatch and roots; Shearman and Beard, 1975; Ledeboer and Skogley, 1967) and reducing the range of plant tissue C to N ratio to 20 to 40 to account for the high litter quality in turfgrass resulting from fertilization and regular mowing. The monthly clipping yield (CRMVST) and aboveground biomass (AGCACC) outputs of the CENTURY model have a unit of g C m^{-2}. We converted them to dry mass by dividing by 0.4268, the average carbon content of Kentucky bluegrass reported by Jo and McPherson (1995).

Table 1. Biomass allocation of Kentucky bluegrass managed under home lawn conditions in northern Colorado.

	Biomass	Annual production†	Standard error	*n*
	kg ha^{-1}			
Clippings‡	4699	4699	251	12
Verdure	3366	1785	321	12
Thatch	8078	4362	371	12
Roots	3247	1753	329	12

† Annual production of clippings = annual accumulative clipping yield; annual production of verdure = biomass of verdure × verdure turnover rate; annual production of thatch = biomass of thatch × thatch turnover rate; annual production of roots = root biomass × root turnover rate. We used the average turnover rates derived by Falk (1976, 1980) for Kentucky bluegrass. Carbon allocation to aboveground and belowground is calculated as annual production of clippings and verdure/annual production of thatch and roots.

‡ Clipping biomass is the cumulative clipping yield of 28 mowing events. Percentage of standing aboveground biomass being removed during each mowing event was calculated by dividing clipping yield of each mowing event by biomass of verdure.

To evaluate the model performance in predicting Kentucky bluegrass monthly clipping yields, we calculated model efficiency (EF), coefficient of determination (CD), mean difference (M), and correlation coefficient (r) based on statistic procedures outlined in Smith et al. (1996, 1997).

In the CENTURY organic matter submodel, fresh organic matter is partitioned into either the structural or metabolic pools based on the lignin to N ratio. When litter (fresh organic matter) decomposes, CO_2 is released and the remaining decomposition product is transferred to one or more SOM pools: active, slow, and passive. The active pool consists of microbes and microbial byproducts and has the most rapid turnover rate. The slow SOM pool represents stabilized decomposition products with an intermediate turnover rate; and the passive pool is recalcitrant SOM with a turnover rate of hundreds or thousands of years. The model assumes that the lignin from plant material goes directly to the slow SOM pool, that soil silt plus clay content influences the amount of C stabilized as slow SOM, and that the formation of passive SOM increases with increasing clay content. The modeled turnover times of these pools are functions of soil texture, soil temperature, nutrient and water availabilities, anoxic conditions, and other factors.

In the N submodel, N flows are considered as a function of C flows and the N content of the recipient SOM pool. The N content of material entering a SOM pool is a function of the soil mineral N pool, with higher C to N ratio for low soil N mineral levels. The N submodel also includes leaching of mineral N, N fertilization, and gaseous losses of N (N_2O, N_2, NO_x, and NH_3). Mineralization occurs when surface and soil microbes and slow SOM decompose, while decomposition of structural plant material results in immobilization (Parton et al., 1993).

The water balance submodel is based on monthly evapotranspiration, water content of the soil, and saturated percolation rates between soil layers.

The CENTURY Model Simulation for Turfgrass Systems

The major input variables for the CENTURY model include (i) soil texture (% sand, clay, and silt); (ii) monthly average maximum and minimum air temperatures; (iii) monthly precipitation and irrigation; (iv) lignin content of plant material; (v) plant tissue C and N ratio and initial soil C; and (vi) soil N inputs through fertilization and atmospheric deposition (Parton et al., 1987; Parton and Rasmussen, 1994). The initial soil organic carbon (0.46, 14.7, and 7.8 Mg C ha^{-1} in active, slow, and passive SOC pools, respectively) was provided by the CENTURY model for cultivated agricultural land in the region.

As the first step, we ran a short-term simulation (15 yr) using the site-specific soil texture, weather data, and management regime (mowing, fertilization, and irrigation) employed in the field experiment. Simulated annual and seasonal clipping yields were compared with measured clipping yields to evaluate the performance of the CENTURY model.

Long-term (100 yr) CENTURY simulations were then conducted using the average precipitation and average minimum and maximum temperatures of a 100-yr weather station record. To generate the best N fertilization regime as functions of the age of turf stand and clipping management, we ran numerous simulations with variable nitrogen rates. We compared model outputs of aboveground biomass, SOC, SON, C to N ratio of SOM, and nitrate leaching under various fertilization rates with clippings removed or returned. Our aim was to select the fertilization regimes that produced a maximum production under the constraint of minimal N leaching. We used aboveground biomass as an indicator of turf quality. As such, the best fertilization rates for different periods after turf establishment under clippings returned or removed scenarios were selected.

RESULTS AND DISCUSSION

Comparison of Measured and Simulated Clipping Yield

Mowing turf to 5.1 cm weekly removed an average of 4.7% of the standing aboveground biomass at each mowing (Table 1). This percentage is higher than that reported in California by Madison (1971), who found that 3% of the aboveground standing biomass was removed at each mowing event.

Simulated clipping yields were compared with the measured clipping yields (Fig. 1). The model correctly simulated the annual clipping yield in 1994, but slightly underestimated annual clipping yields in 1993 and 1995 (Fig. 1A). Model-simulated monthly clipping yields mistimed the seasonal trend, overestimating yields later in the season and underestimating yields early in the season (Fig. 1B). This mistiming trend resulted in a negative EF value (−1.25), a CD value of less than 1 (0.44), and a relatively large M (101.6). The correlation coefficient for the observed vs. simulated clipping yield was −0.32. The mistiming by the CENTURY model may occur because Version 4.0 of CENTURY does not have the ability to simulate photoperiod-induced growth pattern changes. In response to daylength change, bluegrass exhibits more upright growth during the spring (which results in high clipping yields) and more lateral growth during the fall (which results in low clipping yields). Improvement in model performance requires additional information about the seasonal photoperiod effects on C allocation to verdure and clippings. Nevertheless, the CENTURY model simulated annual accumulative clipping yield within 21% of the observed values (Fig. 1A). Previously, we demonstrated that predictions of SOC accumulation by CENTURY compared very well with measured historical SOC data from highly managed turfgrass systems (r = 0.82 to 0.91; EF = 0.67 to 0.57;

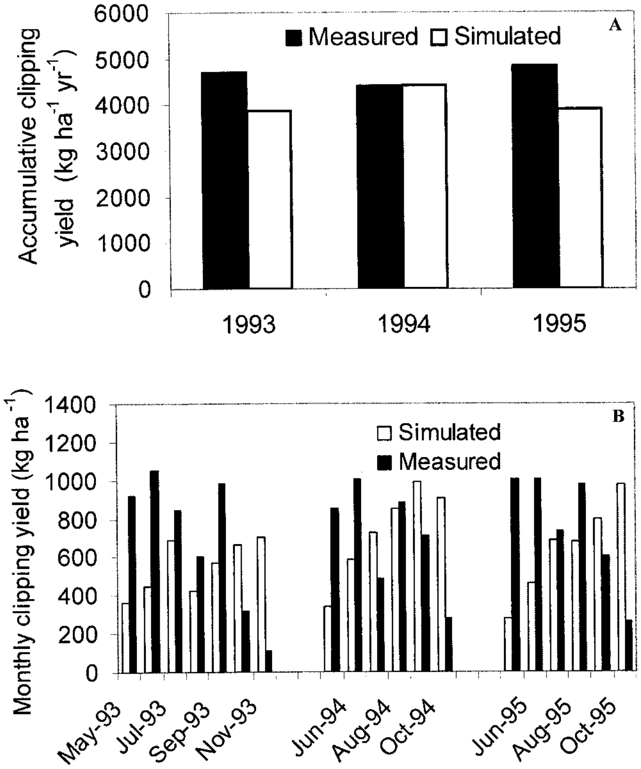


Fig. 1. Comparison of measured and CENTURY-simulated (*A*) annual accumulative clipping yields and (*B*) monthly clipping yields collected from a field study in Colorado. Kentucky bluegrass was managed under typical home lawn conditions.

CD = 2.3 to 3.0; $M = -0.019$ to 6.0) (Bandaranayake et al., 2003). These results suggested that even though monthly variability in clipping biomass was often not well represented, CENTURY is able to simulate different clipping management (clippings retained vs. clippings removed) effects on long-term soil C and N dynamics.

Long-Term Simulation

Long-term simulations were run to examine the effects of different N fertilizer application rates and clipping management regimes on aboveground biomass, SOC, SON, and nitrate leaching for the experimental site. We present the simulation results of four representative management scenarios: the factorial combination of clipping management (removed vs. returned) and two N fertilization levels (150 vs. 75 kg N ha^{-1} yr^{-1}).

Aboveground Biomass

The model predicted that nitrogen availability was very important in ecosystem aboveground productivity. A combination of high fertilization (150 kg N ha^{-1} yr^{-1}) and clipping return would be essential for optimal biomass production (and therefore high turf quality; Fig. 2A). Compared with high fertilization (150 kg N ha^{-1} yr^{-1}) and clipping return management regime, aboveground biomass is predicted to be lower when fertilized at 150 kg N ha^{-1} yr^{-1} N with clippings removed or fertilized at 75 kg N ha^{-1} yr^{-1} N with clippings returned, especially for young turf stands. A low N fertilization coupled with clipping removal would result in a rapid decline of biomass.

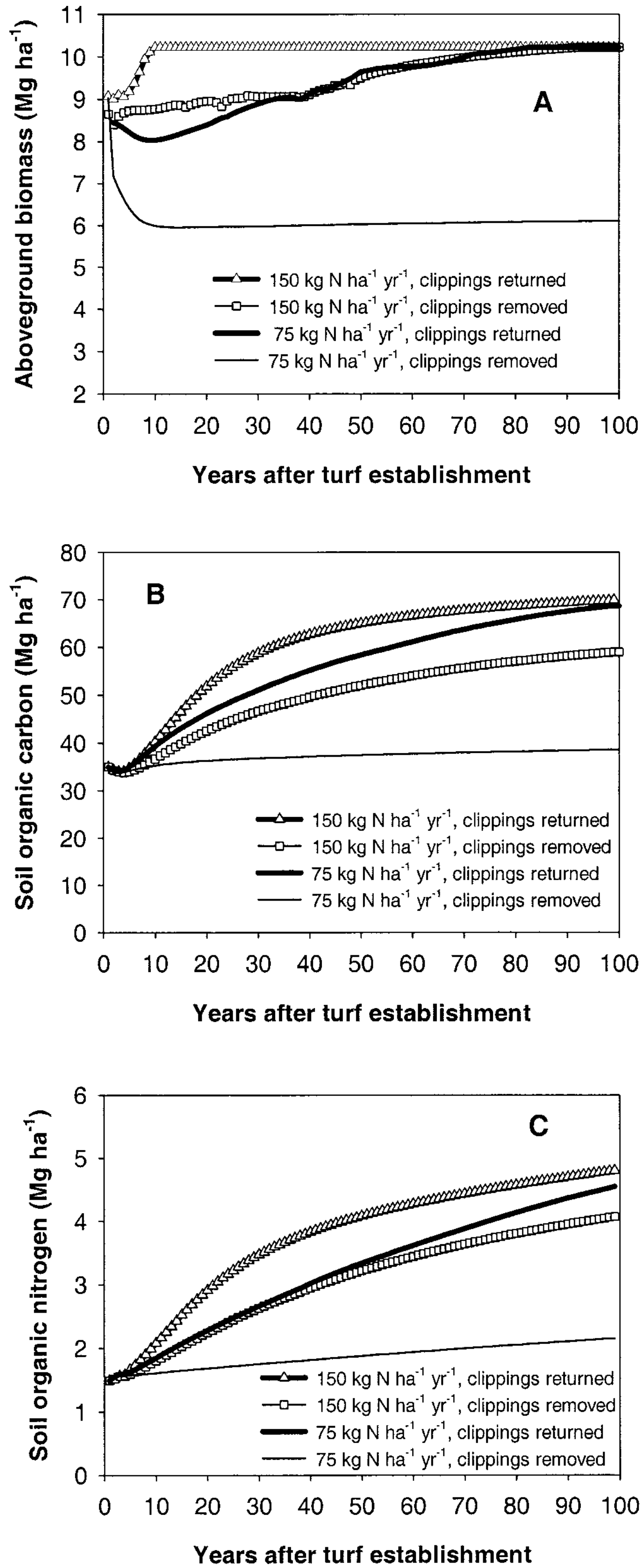


Fig. 2. The CENTURY-simulated long-term effects of clipping management and nitrogen fertilization rate on (*A*) aboveground biomass, (*B*) soil organic carbon, and (*C*) soil organic nitrogen.

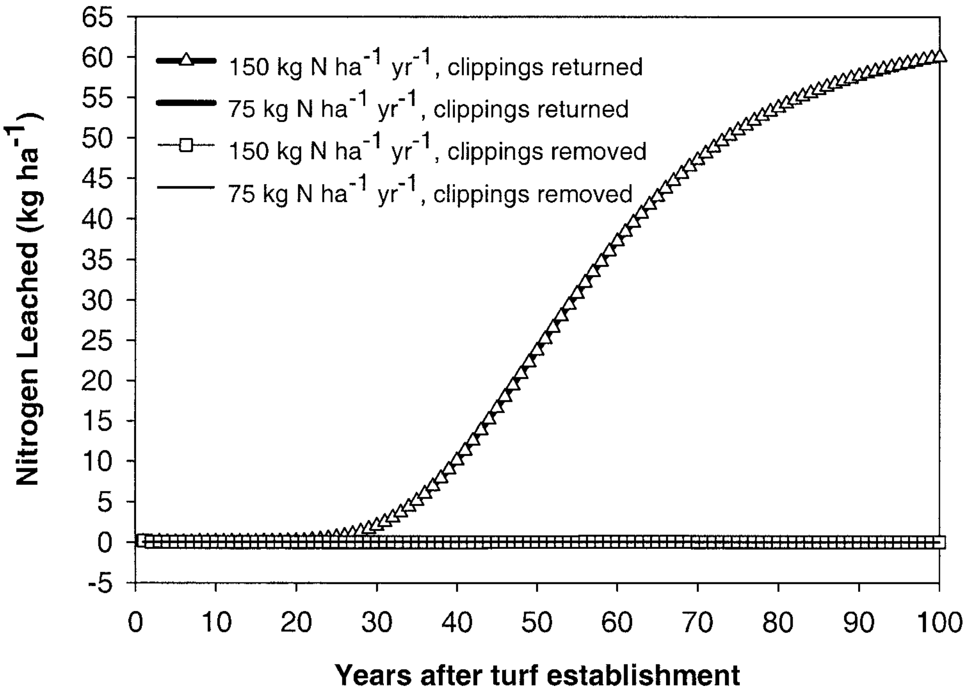


Fig. 3. The CENTURY-simulated nitrate leaching under four management scenarios.

Soil Organic Carbon

Our simulated results indicated that SOC increased with all management scenarios except that of low N fertilization with clippings removal, in which case SOC did not increase after land use was changed to turf. Compared with the clippings removed scenario, returning clippings for 10 to 50 yr would increase soil C sequestration by 11 to 25% under high (150 kg N ha^{-1} yr^{-1}) N fertilization regime and by 11 to 59% under low (75 kg N ha^{-1} yr^{-1}) N fertilization regime. Returning clippings increases carbon sequestration capacity by 14 to 21 Mg ha^{-1} 50 yr after establishment of turf.

With N fertilization at 150 kg ha^{-1} yr^{-1} and the clippings returned scenario, total SOC increased from 34 Mg ha^{-1} at the turf establishment to 65 Mg ha^{-1} about 50 yr after turf establishment. The average rate of accumulation over the 50-yr-period was 0.62 Mg ha^{-1} yr^{-1}. Thereafter, SOC increased very slowly. With N fertilization at 75 kg ha^{-1} yr^{-1} and clippings returned, SOC increased from 34 Mg ha^{-1} at the turf establishment to 65 Mg ha^{-1} within 75 yr after turfgrass establishment. Simulated SOC dynamics showed that high N availability leads to more rapid increases in SOC after turf establishment and faster arrival at the relatively steady state than low N management. Qian and Follett (2002) reported a rapid C sequestration at 0.9 to 1.0 Mg C ha^{-1} yr^{-1} during the first 0 to 25 yr after turfgrass establishment, suggesting the high N availability on the highly managed golf courses.

Soil Organic Nitrogen

Simulated SON exhibited a pattern similar to SOC, with high N application rates leading to more rapid increases in SON after the establishment of turf while returning clippings increased soil N sequestration capacity. The SON increase is slightly and proportionally higher than that of SOC, a reflection of the increase in relative nitrogen content in SOM and a reduction of C to N ratio of SOM over time (Fig. 2B,C). The decreasing soil C to N ratio indicates that the turf ecosystem becomes a more nutrient-rich ecosystem as standing age increases. The CENTURY model predicts that the turf–soil system serves as a strong sink of mineral N. However, the N sink strength gradually decreased with prolonged N or high N application. With best management practices, SOM in the turf ecosystem serves as an important sink of N for several decades. With a 150 kg ha^{-1} yr^{-1} N fertilization rate and clippings returned management scenario, soil N sequestration is approximately 66, 27, and 14 kg N ha^{-1} yr^{-1} during 1 to 30, 31 to 60, and 61 to 100 yr after turfgrass establishment, respectively. Although the N sink strength gradually declines over time, our predictions suggest that turfgrass can maintain sink strength much longer than that reported by Porter et al. (1980), who concluded that SON reached plateau about 10 to 12 yr after turf establishment. A complete vanishing of soil N sink strength within the first decade following establishment of turf was a key assumption made in a model simulation by Valiela et al. (1997), who concluded that 39% of applied fertilizer N would be lost via gaseous forms and 61% would reach the subsoil, resulting in significant leaching.

Nitrate Leaching

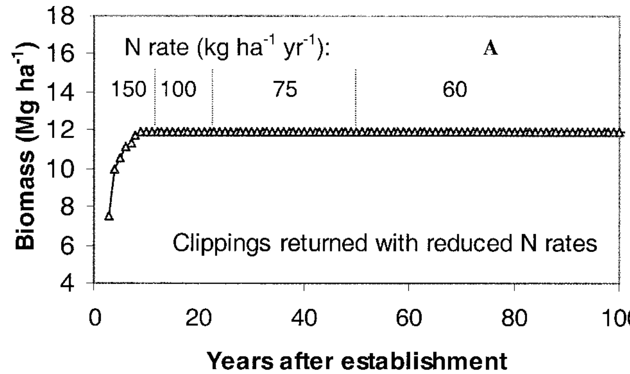
The CENTURY model predicted that N leaching would be minimal (close to nonexistent) under the management scenarios of low N fertilization or high N rate with clippings removed (Fig. 3). With a 150 kg ha^{-1} yr^{-1}

N fertilization rate and clippings returned scenario, N leaching is minimal (close to nonexistent) 20 to 30 yr after turf establishment. These results are consistent with the research findings of many studies conducted on newly established turf plots (<10 yr old; Petrovic, 1990). The model predictions indicate that minimal nitrate leaching occurred during the period of rapid carbon sequestration. This suggests that SOC accumulation would tie up soil mineral N and result in a rapid accumulation of SON. As the rate of carbon sequestration declined, less applied N was tied up in the SOC. Therefore, with time, an increasing amount of applied mineral N (NO_3) is available for gaseous loss and/or leaching, if the fertilization regime is unchanged. Continuously high fertilization and clipping return would result in increased nitrate leaching, reaching 50 to 60 kg ha^{-1} yr^{-1} when turf reaches 100 yr. Fertilization rates higher than 150 kg ha^{-1} yr^{-1} can lead to significant N leaching that occurs earlier. These simulation results suggest that following a period of clipping return, N fertilization should be reduced, otherwise N loss would increase over time.

Optimal Nitrogen Fertilization Rates as a Function of Turf Ecosystem Age and Clipping Management

We examined opportunities for reducing N fertilization by comparing simulated biomass and N leaching at various fertilization rates with clippings removed or returned. The CENTURY model predicted that, as the age of a turf ecosystem increases, N application rates should be reduced to balance the greater amounts of N mineralized from SOM. At a loam soil site and under a clipping-returned scenario, the CENTURY model predicts that optimal productivity and low N leaching (<2 kg N ha^{-1} yr^{-1}) are obtained at annual N fertilization rates of 150, 100, 75, and 60 kg N ha^{-1} during 1 to 10, 11 to 25, 26 to 50, and 51 to 100 yr after turfgrass establishment, respectively (Fig. 4A,B). In contrast, under the clippings removed scenario the model suggests that N fertilization at 200, 150, and 140 kg N ha^{-1} yr^{-1} would be required for the periods of 1 to 15, 16 to 50, and 51 to 100 yr after turfgrass establishment, respectively, to achieve a comparable productivity and turf quality (Fig. 4B). Fertilization below these rates would be insufficient for maximum biomass production and desired turf quality.

Our simulation results suggest that N application to turfgrass systems can be reduced over time and the reduction should be greater where clippings are returned. In addition, returning grass clippings to the turf–soil ecosystem can reduce N requirements by 25% between 1 to 10 yr after turf establishment, 33% between 11 to 25 yr after establishment, 50% between 25 to 50 yr after establishment, and 60% thereafter (Fig. 4A). These amounts of reduction in N fertilization, along with clipping return, could result in a substantial reduction of nitrate leaching and gaseous loss of nitrogen.



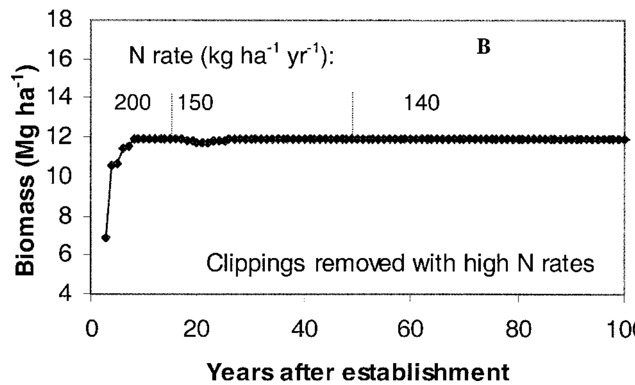


Fig. 4. The CENTURY-simulated annual aboveground biomass under two management scenarios: (*A*) clippings returned and annual fertilization rates of 150, 100, 75, and 60 kg N ha^{-1} during 1 to 10, 11 to 25, 26 to 50, and 51 to 100 yr after turfgrass establishment, respectively; and (*B*) clippings removed and annual fertilization rates of 200, 150, and 140 kg N ha^{-1} for the periods of 1 to 10, 11 to 50, and 51 to 100 yr after turfgrass establishment, respectively.

CONCLUSIONS

The CENTURY simulation model offers an opportunity to couple C and N processes and study long-term effects of turfgrass clipping management on biomass production, N requirements, SOC and SON content, and N leaching. The CENTURY model predicted that, following establishment, turf–soil systems have great potential to sequester C. Rapid carbon sequestration retains mineral N as SON in a young turf stand. Thus, the turf–soil systems serve as a strong N sink. However, the N sink strength gradually decreased with a prolonged or high rate of N application.

Clipping input plays an important role in C and N sequestration, and consequently, in ecosystem sustainability. Net carbon and nitrogen sequestration can be increased by returning clippings to turfgrass ecosystems. Returning clippings offers opportunities for reducing N fertilization requirements by 25 to 60%, depending on the duration of the practice, without a loss of turf quality as indicated by aboveground biomass. In addition to 25 to 60% fertilization reduction, long-term return of clippings increased SOC and SON pools. The CENTURY model simulation suggests that, by reducing N fertilization as the age of turf stand increases, it is possible to maintain desired turf quality with minimal long-term N leaching (<2 kg N ha^{-1} yr^{-1}). Further field research is needed to test the model with long-term measurements of SON, SOC, and nitrate leaching as affected by clipping and fertilization management.

REFERENCES

Bandaranayake, W., Y.L. Qian, W. Parton, D.S. Ojima, and R.F. Follett. 2003. Estimation of soil carbon sequestration in turfgrass systems using the CENTURY model. Agron. J. 95:558–563.

Carter, M.R., W.J. Parton, I.C. Rowland, J.E. Schultz, and G.R. Steel. 1993. Simulation of soil organic carbon and nitrogen changes in cereal and pasture systems of southern Australia. Aust. J. Soil Res. 31:481–491.

Falk, J.H. 1976. Energetics of a suburban lawn ecosystem. Ecology 57:141–150.

Falk, J.H. 1980. The primary productivity of lawns in a temperate environment. J. Appl. Ecol. 17:689–696.

Food and Agricultural Organization. 2002. FAOSTAT: Agricultural data. Available online at http://apps.fao.org/page/collections?subset=agriculture (verified 28 Apr. 2003). United Nations FAO, Rome.

Harivandi, M.A., W.L. Hagan, and C.L. Elmore. 2001. Recycling mower effects on biomass, nitrogen recycling, weed invasion, turf quality, and thatch. Int. Turfgrass Soc. Res. J. 9:882–885.

Heckman, J.R., H. Liu, W. Hill, M. Demilia, and W.L. Anastasia. 2000. Kentucky bluegrass responses to mowing practice and nitrogen fertility management. J. Sustainable Agric. 15:25–33.

Intergovernmental Panel on Climate Change. 1997. Agriculture: Nitrous oxide from agricultural soils and manure management. Chapter 4. *In* Intergovernmental Panel on Climate Change guidelines for national greenhouse gas inventories. Organisation for Economic Cooperation and Development, Paris.

Jo, H.K., and E.G. McPherson. 1995. Carbon storage and flux in urban residential greenspace. J. Environ. Manage. 45:109–133.

Kelly, R.H., W.J. Parton, G.J. Crocker, P.R. Grace, J. Klir, M. Korschens, P.R. Poulton, and D.D. Richter. 1997. Simulating trends in soil organic carbon in long-term experiments using the CENTURY model. Geoderma 81:75–90.

Kopp, K.L., and K. Guillard. 2002. Clipping management and nitrogen fertilization of turfgrass: Growth, nitrogen utilization, and quality. Crop Sci. 42:1225–1231.

Ledeboer, F.B., and C.R. Skogley. 1967. Investigations into the nature of thatch and methods for its decomposition. Agron. J. 59:320–323.

Madison, J.H. 1971. Practical turfgrass management. Van Nostrand Reinhold Co., New York.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton. 1993. CENTURY soil organic matter model environment. Technical documentation. Agroecosystem Version 4.0. Great Plains System Res. Unit Tech. Rep. 4. USDA Agric. Res. Serv., Fort Collins, CO.

Mosier, A.R., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput. 1998. Closing the global N_2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle. Nutr. Cycling Agroecosyst. 52:225–248.

Parton, W.J., and P.E. Rasmussen. 1994. Long-term effects of residue management in wheat–fallow: I. Century model simulations. Soil Sci. Soc. Am. J. 58:530–536.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51:1137–1179.

Parton, W.J., J.M.O. Scurlock, D.S. Ojima, T.G. Gilmanov, R.J. Scholes, D.S. Schimel, T. Kirchner, J.C. Menaut, T. Seastedt, E. Garcia Moya, A. Kamnalrut, and J.I. Kinyamario. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycles 7:785–809.

Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19:1–14.

Porter, K.S., D.R. Bouldin, S. Pacenka, R.S. Kossack, C.A. Shoemaker, and A.A. Pucci, Jr. 1980. Studies to the fate of nitrogen applied to turf: Part I. Research project technical complete report. OWRT Project A-086-NY. Cornell Univ., Ithaca, NY.

Qian, Y.L., and R. Follett. 2002. Assessing soil carbon sequestration in turfgrass soil using long-term soil testing data. Agron. J. 94:930–935.

Shearman, R.C., and J.B. Beard. 1975. Turfgrass wear tolerance mechanisms. Effects of cell wall constituents on turfgrass wear tolerance. Agron. J. 67:211–215.

Smith, J.U., P. Smith, and T.M. Addiscott. 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models. p. 183–202. *In* D.S. Powlson, P. Smith, and J.U. Smith (ed.) Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Ser. I. Vol. 38. Springer-Verlag, Heidelberg, Germany.

Smith, P., J.U. Smith, D.S. Powlson, W.B. McGill, J.R.M. Arah, O.G. Chertov, K. Coleman, U. Franko, S. Frolking, D.S. Jenkinson, L.S. Jensen, R.H. Kelly, H. Klein-Gunnewiek, A.S. Komarov, C. Li, J.A.E. Molina, T. Mueller, W.J. Parton, J.H.M. Thornley, and A.P. Whitmore. 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81:153–225.

Starr, J.L., and H.C. DeRoo. 1981. The fate of nitrogen fertilizer applied to turfgrass. Crop Sci. 21:531–536.

USEPA. 1999. Background report on fertilizer use, contaminants, and regulations. Natl. Program Chemicals Division, Office of Pollution Prevention and Toxics, Washington, DC.

Valiela, I., G. Collins, J. Kremer, K. Lajtha, M. Geist, B. Seely, J. Brawley, and C.H. Shaw. 1997. Nitrogen loading from coastal watersheds to receiving estuaries: New method and application. Ecol. Appl. 7:358–380.